SIGNIFICANCE OF CARBONATE CONCRETIONARY GROWTHS ON A MOA BONE IN HOLOCENE TIDAL FLAT DEPOSITS BENEATH AUCKLAND CITY, NEW ZEALAND

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Abstract. A bone of the moa *Anomalopteryx didiformis* (Owen), dated at 7520 ± 150 years B.P. (NZ3088B) and contained in 7500-6500 years B.P. tidal flat deposits beneath down-town Auckland city, had carbonate concretionary growths about its articular ends. The concretions, which are younger than about 6500 years B.P., were formed by precipitation of microgranular, relatively low-magnesian (6-8 mol% $MgCO_3$) calcite cement within pore waters of the sandy mud enclosing the bone, probably associated with bacterial decomposition of associated organic matter. A variety of evidence suggests that generally similar carbonate concretions encasing macrofaunal remains are relatively widespread in Holocene shore-line sediments of Waitemata Harbour, Auckland, especially in the vicinity of old buried stream channels. Precipitation of low-magnesian calcite cement into very early diagenetic concretions appears to be especially characteristic of several Holocene coastal marine deposits in essentially temperate latitude, cool water localities in both southern and northern hemispheres.

During construction of foundations for the South Pacific Hotel, Customs Street, Auckland, in 1969, the building supervisor on the project, Mr K. Goss, retrieved a moa bone from a drag-line bucket excavating in soft, greenish grey, shelly mudstone. He recorded the position of the sample with respect to both present street level and a layer of *in situ* stones in the pit marking the pre-1900 sea bed of the old Customs Street Wharf, which was subsequently buried by land reclamation in 1880-90 (Fig. 1, Barr 1922). The bone was forwarded to Auckland Institute and Museum in 1970 and was identified by Mr R.L. Scarlett (Canterbury Museum) as the femur of one of the most widely distributed Quarternary moa species, *Anomalopteryx didiformis* (Owen). The bone was brought to our attention by the then Director of the Museum, Mr E.G. Turbott, and offered for study. We undertook to investigate the nature of concretionary growths about its articular ends, and to have it dated to help elucidate the stratigraphy of the shallow marine deposits beneath down-town Auckland city.

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Stratigraphy

The general stratigraphic succession beneath the intersection of Customs Street and Queen Street in down-town Auckland is known from drill cores obtained during preliminary site investigations for an underground terminal for a proposed Auckland Rapid Transit scheme (Anon. 1974). A schematic west to east section along Customs Street, in the vicinity of South Pacific Hotel, is presented (Fig. 1) from drill core data.

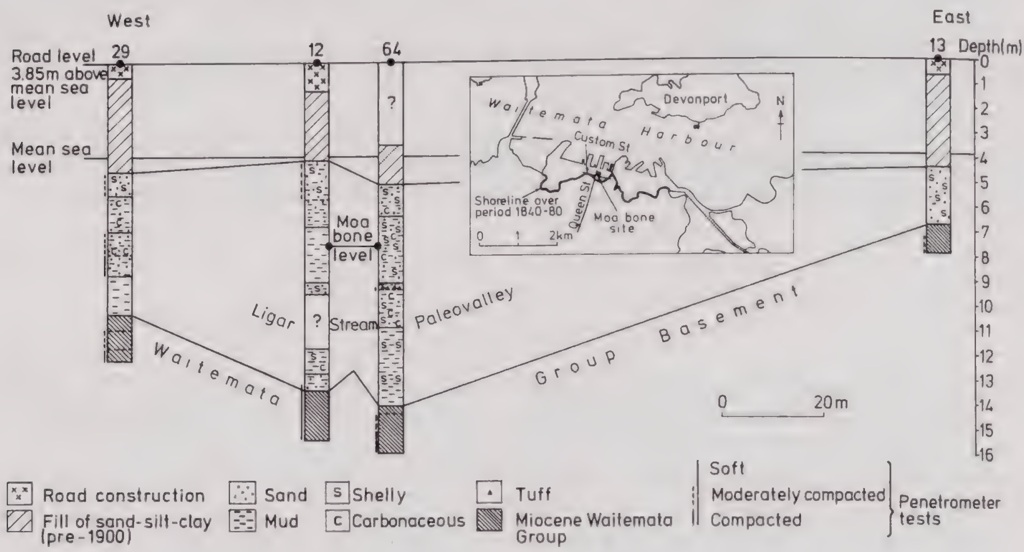

Fig. 1. Subsurface stratigraphy (based on Anon. 1974) in the vicinity of South Pacific Hotel, immediately east of the intersection of Customs Street and Queen Street, down-town Auckland city, showing level from which the moa bone was collected. Inset shows locality map, and heavy line traces the approximate position of Auckland waterfront from 1840-80, prior to major reclamation (after Barr 1922).

Approximately 4 m of road construction materials and pre-1900 fill of clay and blocks of sandstone and mudstone overlie 2-10 m of muds, sandy muds, muddy sands, and sands, commonly shelly and locally carbonaceous or woody, which in turn rest on local basement, Early Miocene flysch deposits of Waitemata Group. Basement topography defines a narrow paleovalley, the Ligar Stream valley, plunging northwards in the sub-surface towards the modern Waitemata Harbour. The fill of shelly muds and sands thins to the east and west away from the axis of the paleovalley and there is also an overall increase in thickness and degree of weathering of the residual soil or regolith capping the basement flysch in the same directions. The approximate stratigraphic level from which the moa bone was collected is marked on Bores 12 and 64 (Fig. 1).

A more detailed examination of the core from Bore 64 indicates that the fauna in the muddy sands beneath the basaltic tuff at 9.3 m depth consists mainly of scattered broken shell fragments, including recognisable *Chione* remains, each only a few millimetres across. Interbedded mud layers preserve rootlet structures. Fragmented shells occurring in layers in muds in the lowest part of the core (10-14 m) are extremely decayed and chalky. The 10 cm thick basaltic tuff is immediately overlain by 20 cm of grey, weakly laminated mud containing rootlets. The sequence of muddy fine sands and sandy muds from 5-9 m, which includes the moa bone, contains considerable plant debris and a moderately rich fauna, dominated completely by the cockle *Chione (Austrovenus) stutchburyi* (Wood), but including *Zeacumantus lutulentus* (Kiener), *Tellina (Macomona) liliana* Iredale, *Cominella adspersa* (Bruguière), and possibly *Nucula hartvigiana* Pfeiffer and *Amphibola crenata* (Gmelin). Shells are generally fresh and retain their coloration, and many are broken but unabraded; some *Chione* valves remain articulated. The fauna is that of a protected mixed sand-mud tidal flat environment, possibly somewhat brackish, not dissimilar to some of the lower energy embayments presently found around the Waitemata Harbour (for example, Shoal Bay and Hobson Bay).

Presumably, the moa bone was washed onto the estuarine paleo-flats by Ligar Stream, or alternatively the moa may have died at the coast line with eventual dispersal of its bones across the embayment by marine currents. Searle (1964) has intimated that fairly large numbers of moa probably lived on the Auckland isthmus during the latest Pleistocene and early Holocene.

Description of bone and concretions

The bone (Fig. 2; fossil record no. N42/f670), was 220 mm long, well preserved, and had a brownish cortical surface due to incipient iron-staining. Nodular, light grey concretionary material, essentially a hard calcareous mudstone, adhered strongly to parts of both ends of the bone (Fig. 2). The concretionary growths roughly paralleled the bulbous outlines of the articular ends of the bone, reached a maximum thickness of 7 mm, and included a few small specimens of the cockle *Chione (Austrovenus) stutchburyi* (Wood).

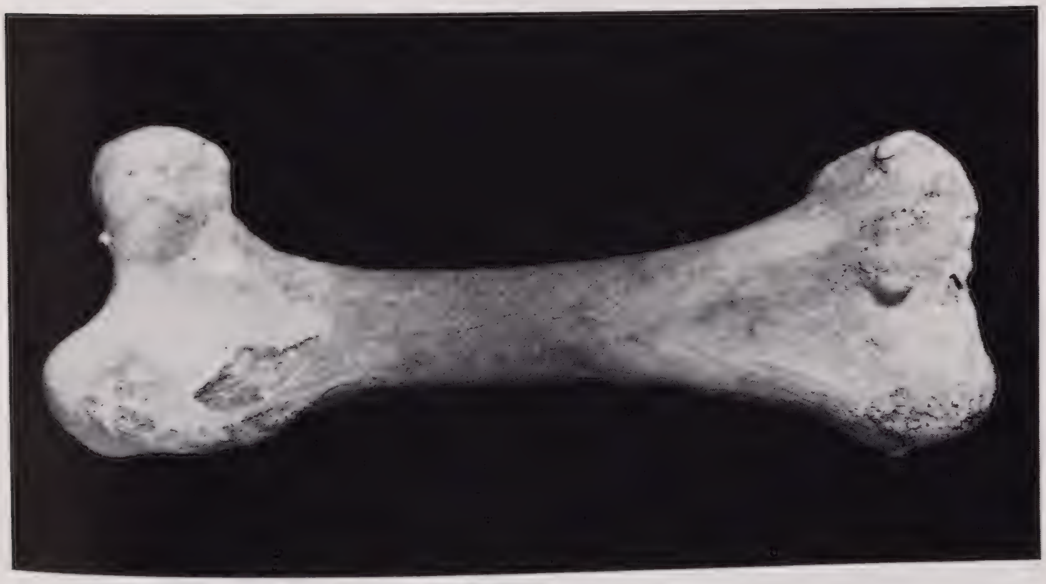

Fig. 2. Femur of the moa *Anomalopteryx didiformis* (Owen) showing carbonate concretionary growths encasing a few small cockles about its articular ends. Length of bone: 220 mm.

X-ray diffraction analysis (Chave 1952, Nelson & Cochrane 1970) indicates that the *Chione*-free concretionary material consists of about 30-40% of the clay minerals illite and chlorite, 30-35% calcite containing some 6-8 mol% $MgCO_3$ (that is, relatively low-magnesian calcite of Friedman & Sanders 1978), 15% quartz, 5% plagioclase feldspar and small amounts of ferromagnesian minerals and carbonate-apatite, the last named component possibly resulting from inclusion of bone fragments in the analysis. Apart from the presence of abundant calcite, the composition is broadly similar to that of the soft shelly mudstone encasing the bone, indicating that the concretionary material owed its existence to the precipitation of calcite within pores of the sediment adjacent to the ends of the bone. In thin-section the calcite appears as a pasty, cryptocrystalline to microcrystalline granular cement which blends into, and is largely irresolvable from, the fine-grained argillaceous matrix of the concretion. Subangular grains of silt to fine sand sized quartz, feldspar, and fine-grained rock fragments, together with small shell chips, are scattered through this matrix.

Origin of concretions

Carbonate concretions commonly develop during early stages of sediment diagenesis about decaying organisms, such as fish, molluscs, or plant fragments (for example, McCunn 1972, Engelhardt 1977, Hayes & Franks 1978). Bacterial decomposition results in formation of amines and ammonia which locally increase the alkalinity of pore waters to a level where carbonate precipitation is possible about the organic nucleus (Berner 1968). Such an origin is tenable for the present case. Preferential development about the articular ends of the bone may be related to accelerated exchange of solutions and gases along the length of the bone shaft via the porous, medial medullary cavity. Most active diffusion of calcium and bicarbonate ions in pore waters of the surrounding sediment would occur along concentration gradients disposed radially about the ends of the bone, leading ultimately to inorganic precipitation of relatively low-magnesian calcite cement in sediment immediately adjacent to the bone ends. The source of dissolved ions was possibly from the selective dissolution of certain metastable aragonitic skeletal fragments in the enclosing or underlying deposits (Nelson 1978), such as is evidenced by the soft, decayed, and generally poorly preserved nature of shells in the lower section of Bore 64 (Fig. 1). Selective alteration of skeletons implies that pore solutions have been locally undersaturated in calcium carbonate, resulting perhaps from the subsurface injection of fresh groundwaters down the Ligar paleovalley and into the coastal marine sediments burying it.

Age of bone and concretions

The entire sample (Fig. 2) was forwarded to Instititute of Nuclear Sciences, Lower Hutt, in the hope that two radiocarbon dates might be obtained, one from the bone collagen and the other from the carbonate concretions. Unfortunately there proved to be insufficient sample to date the carbonate and this material was subsequently inadvertently mislaid at that institute. The moa bone itself yielded a radiocarbon age of 7520 ± 150 years B.P. (NZ3088B) based on new half life data, or 7300 ± 150 years B.P. (NZ3088A) based on old half life calculations (latter age reported also by McCulloch & Trotter 1979).

This bone age places a maximum age on the concretionary growths, but from sea-level evidence it is probable that the carbonate concretions are somewhat younger than 7500 years old. During this period Holocene sea level was rising rapidly (Fairbridge

1961). Most eustatic sea-level curves for the Holocene place sea level of 7500 years ago some 10-20 m below present (for example, Curray *et al.* 1970), while a curve proposed by Schofield (1964) for New Zealand indicates that sea level was down about 12 m at this time, a height supported by recent numerical modelling procedures (Clark & Lingle 1979, fig. 10). These data suggest that Ligar Stream valley is unlikely to have been drowned 7500 years ago and that its fill of marine sediments must post-date this age. There is ample evidence that mean sea level in northern New Zealand some 4000 years ago stood *ca.* 2 m above its present position (Searle 1964, Schofield 1973, 1975, Marks & Nelson 1979). Assuming a linear rate in rise of sea level between the −12 m and +2 m levels, and applying the modern tidal range figure at Auckland of *ca.* 2.5 m, then the intertidal deposits containing the moa bone at 4 m below present mean sea level formed 5500 ± 300 years ago. However, a linear rate of sea level rise from 7500 to 4000 years B.P. is probably an oversimplification. For example, from north of Auckland, Schofield (1973) dated shelly muds of likely intertidal origin, which formed close to modern sea level, at about 6500 years B.P. On this basis the Customs Street moa bone deposits could be as old as 6800 ± 100 years B.P., an age consistent with the predicted −4 m sea level height from numerical modelling (Clark & Lingle 1979), and perhaps more in keeping with the bone date of approximately 7500 years B.P. Until such time as sufficient amounts of well preserved shell material are available from the deposits themselves for radiocarbon dating, it is concluded that their age lies in the range 7000-5000 years B.P., probably closer to the older date. The calcite cement forming the concretions must therefore be younger than about 6500 years B.P.

Discussion

The carbonate concretionary material described here is not an isolated occurrence in the marine Holocene sediments of the Auckland region. Bartrum (1917) described and figured numerous carbonate concretions dredged from comparable depths beneath the bed of the Waitemata Harbour. The concretions formed irregular nodular masses, from 1 to 15 cm or more in size, and included a variety of molluscan shells, small crabs, and wood fragments. Bartrum (1917) argued that the microgranular carbonate cement was precipitated directly from sea water, probably being (p.427) ". . . initiated by the decomposition of the organic matter in the epidermis of molluscs such as *Atrina* and the hard parts of the crabs".

Discussing the results of a marine seismic reflection survey in shallow waters in upper Waitemata Harbour, Hicks & Kibblewhite (1976) recorded two anomalous features associated with the fill of Recent marine sediments: the local occurrence of a strong reflector horizon within the top 2 m of sea bed, which could not be related to any change in physical properties of the sediments as revealed by augering or coring; and occasional acoustically opaque zones, which they interpreted as due to gas bubbles occurring within the sediment. Similar features have also been observed by High & Cornwell (1974) using the same seismic equipment in central Waitemata Harbour. It is interesting to speculate that the unexplained strong reflector horizons recorded by these workers are due to discontinuous layers of carbonate concretions in the Holocene sediments which would not necessarily be tapped or captured by drilling. Hicks & Kibblewhite (1976) further noted that all sites exhibiting the anomalous features are located by old buried stream channels. Significantly, Bartrum (1917) showed that the concretion-bearing sediments he studied (p.428) ". . . occur in a steep-walled narrow gut . . . a continuation of the well-marked gulch spanned by Grafton Bridge'', and our concreted moa bone comes from the marine sediment fill of Ligar Stream paleovalley. The interstitial gases producing the acoustically opaque zones in some estuarine sediments are probably derived from degradation of abundant organic matter in the deposits (Schubel 1974). It is possible that it is these gases which are responsible for selective dissolution of skeletal carbonate materials at certain times, and inorganic precipitation of calcite cement to form concretions at other times, depending on the relative abundances and reactivity of carbon dioxide, ammonia, and amines produced during decomposition of organic matter (Engelhardt 1977). In this manner the association of carbonate concretions with acoustically turbid zones and strong reflector layers in shallow subsurface deposits of coastal embayments at Auckland may not be altogether fortuitous.

Carbonate-rich concretions enclosing a variety of different faunal types, including a moa bone (Fleming 1963), are known from off-shore Quaternary shallow marine and estuarine deposits elsewhere in New Zealand (Finlay & Benson 1950, Fleming 1951, 1963, Pantin 1958, Sherwood & Nelson 1979). Overseas examples of Holocene concretions in shore-line deposits resembling the New Zealand occurrences include those described by Etheridge & McCulloch (1916) from coastal Australia, by Weeks (1957) from coastal Greenland and Canada, by Garrison *et al.* (1969) from west coast of Canada, by Brown & Farrow (1978) from west coast of Scotland, and by Bromley (pers. comm. cited in Brown & Farrow 1978) from Swedish North Sea coast. Common to most of these occurrences is their temperate latitude, cool water aspect, and the presence of calcite rather than aragonite as the calcium carbonate cement in the concretions (cf. Nelson 1978).

Conclusions

1. A femur of the moa *Anomalopteryx didiformis* (Owen) in tidal flat deposits beneath down-town Auckland city has been radiocarbon dated at 7520 ± 150 years B.P. (NZ3088B).
2. The associated sandy muds, which are both shelly and carbonaceous, formed when mean sea level was *ca.* 4 m below present, probably at some time from 7500 to 6500 years B.P.
3. Sometime after 6500 years B.P. carbonate concretions formed about the articular ends of the moa bone by precipitation of relatively low-magnesian (6-8 mol% $MgCO_3$) calcite cement within pore waters of the immediately adjacent sediment, probably associated with bacterial decomposition of organic matter in the bone.
4. Carbonate concretions enclosing a variety of macrofauna are recorded elsewhere from bottom sediments of Waitemata Harbour and probably have a generally similar age and diagenetic origin to the concreted moa bone. Moreover, it is suggested that previously unexplained strong seismic reflector horizons within a couple of metres of the sea bed in Holocene marine sediments in several areas of the harbour, especially in the vicinity of old buried stream channels, may be due to the existence of laterally discontinuous layers of these carbonate concretions.
5. The concretions demonstrate that it is possible for relatively low-magnesian calcite to precipitate directly as a microgranular cement from pore waters in shallow marine deposits at a very early stage of diagenesis. Carbonate concretions of this type,

containing a cement of essentially diagenetically stable low-magnesian calcite, rather than metastable aragonite or high-magnesian calcite, appear to be most characteristic of various Holocene coastal deposits in temperate latitude, cooler water localities in both southern and northern hemispheres.

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